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Upgrading of woody biomass by torrefaction under pressure

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ABSTRACT

In this study, the upgrading by torrefaction of leucaena, woody biomass, at 200–250 °C under volumetric pressure up to 4 MPa was examined. It was found that the yield of torrefied leucaena decreased with the increase in torrefaction temperature, whereas at the same temperature the yield of torrefied leucaena increased with the increase in torrefaction pressure. From the elemental analyses, the higher carbon content in torrefied leucaena can be achieved by the rising of torrefaction pressure. As large as 92.6% of carbon was recovered in the torrefied leucaena prepared at 250 °C and 4 MPa. On the other hand, the oxygen content decreased to 31.1% for the leucaena torrefied at 250 °C and 4 MPa. The higher heating value (HHV) of leucaena torrefied at high pressure increased significantly when compared to that of leucaena torrefied at atmospheric pressure. As large as 94.3% of energy yield was achieved with the mass yield of 74.4% for the torrefaction at 250 °C and 4 MPa. From the subsequent pyrolysis and combustion in TGA, leucaena torrefied under pressure showed the difference of weight decreasing curves comparing to that of leucaena torrefied at atmospheric pressure. It was found that the weight of leucaena torrefied at high pressure started to decrease at temperature lower than 200 °C. The char yield at 800 °C for the leucaena torrefied at high pressure increased with the increase in torrefaction pressure. These results suggested that the structure of leucaena was changed by the torrefaction under pressure and the cross-linking reactions during the pyrolysis were enhanced by the pressure during the torrefaction resulting in increase in char yields. The substantial increase in char combustion rate was also found for leucaena torrefied under pressure.

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1. Introduction

Due to the global warming situation over the excessive using of fossil fuel worldwide, the utilization of renewable energy sources has thus become increasingly of interest. Biomass is one of the renewable resources which have received growing attention nowadays, especially in thermo-chemical conversion applications, such as pyrolysis, combustion, gasification and co-gasification/combustion. This is because biomass is considered as a carbon neutral fuel and it also emits less sulfur compared to fossil fuel when it is combusted. However, biomass is classified as a low-grade fuel which naturally contains undesired properties, such as high moisture content, high ash content and low energy density. Thus, direct utilization of biomass seems to face great barriers overcoming the above drawbacks.

Torrefaction is one of the thermal treatment techniques at relative low temperature range of 200–300 °C in an inert atmosphere, which aims to improve the fuel properties attractively for further utilization such as combustion, gasification and/or co-combustion. Several studies have been conducted on the properties of torrefied biomass including woody and non-woody biomass by varying temperature and holding time during torrefaction. It was found that the energy density as well as the higher heating value (HHV) was increased progressively at higher torrefaction temperature and at longer holding time [1–10,24]. This is due to the rising of carbon and reducing of oxygen content in biomass. The torrefied biomass structure was also found to become more hydrophobic [11,12]. The improvement of grindability of torrefied biomass which seems to be the feature for this technique was reported. The using of torrefied biomass therefore significantly reduced the size reduction cost, operating and maintenance cost in the term of less energy consumption for grinding [3,13–16]. During torrefaction, kinetic studies have been conducted through several reactors and scales in order to predict the solid behaviors inside the reactor [3,17–21]. The further pyrolysis, combustion and gasification behaviors were also found to improve through the using of torrefied biomass [7,12,22–25].

As the previous studies showed, most of the studies were performed at atmospheric pressure in which although the biomass properties were found to improve significantly, the relatively low

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yield comparing to the gained calorific value of torrefied biomass tends to be the limitation. In the view point of elemental properties of torrefied biomass, although oxygen content was decreased substantially during torrefaction, carbon content was also removed in the form of CO_2 and condensable products as well. Additionally, by rising of torrefaction temperature, the losing of carbon will be increased unavoidably resulting in the reducing of solid yield as well as the energy yield. Thus, in order to solve these drawbacks, the pressure applied during torrefaction seems to be one of the solutions proposed although it is quite difficult to operate torrefaction under pressure. To date, few studies have been conducted to examine the effect of pressure on the biomass properties during pyrolysis. Mok and Antal [26] investigated the product during pyrolysis of cellulose under pressure up to 0.6 MPa at 500 °C. They reported that the increase of pressure resulted in the increasing of char yields and CO_2. On the other hand, the CO, CH_4, C_2H_6 and C_3H_6 were found to decrease. The formation of cellulose char was found to favor by the increase in the volatile residence time. Miura et al. [27] successfully prepared the high strength activated carbon from biomass wastes carbonizing under mechanical pressure. The biomass wastes were pressed at 10 MPa under inert atmosphere by using mechanical pressure at the temperature range around 25–300 °C. They suggested that cellulose played the important role to increase char yield and to develop pore structure. Recently, Cetin et al. [28] investigated the char reactivity of radiata pine char prepared at pressure between 0.1 MPa and 2 MPa and temperature between 800 and 1000 °C. They found that the char gasification reactivity decreased due to the destruction of micropore structure from the high pressure during char preparation. As shown from the previous reports, lack of studies focused on the pressure affecting biomass properties at torrefaction regime. The study of thermo conversion behaviors of biomass upgraded under pressure such as pyrolysis and combustion are also rather limited.

In this study, the volumetric pressure has been applied during the torrefaction of woody biomass. The woody biomass used in this study was *Leucaena leucocephala*, the fast growing tree which normally considered as one of the most potential energy crops in Thailand [29]. Leucaena has been torrefied at low temperature at atmospheric pressure and under pressure up to 4 MPa in inert atmosphere. Throughout the torrefaction, properties of the torrefied leucaena were investigated. Moreover, the pyrolysis and combustion behaviors of leucaena torrefied under pressure have been examined in details.

2. Materials and experimental procedure

2.1. Materials

Woody biomass (*L. leucocephala*) was used as a sample in this study. It was first shredded with a cutting mill and ground with a ball mill in order to obtain a sample particle size less than 75 μm. Then, the sample was dried in vacuum oven at 70 °C for 24 h before the experiments.

2.2. Experimental set-up for torrefaction

Fig. 1 shows the schematic diagram of the torrefaction experimental unit used for this study. The reactor is made of stainless steel with the outside diameter of 12.7 mm and 150 mm in length. The reaction temperature is measured by the thermocouple placed inside the reactor, close to the sample. The pressure transducer is connected at the top end of the reactor in order to monitor the change of pressure in real time during the experiment.

On each run, fine sample of around 150 mg was placed in the 150 mm-length stainless steel reactor. The helium (99.999% purity) was then purged into the reactor in order to remove the air inside for several times. The furnace was then heated up to the desired temperature (200 °C, 225 °C and 250 °C). Then, the reactor was placed in the middle of the furnace. After reaching the desired temperature, the reactor was held for 30 min. For torrefaction under pressure, the desired pressure inside the reactor was controlled by the initial compressing of helium into the reactor at certain values before starting the experiment. Then, the pressures reached the desired conditions within 10 min and were maintained throughout the experiment. For torrefaction at atmospheric pressure, the valve at the top of the reactor was opened allowing the gas flow into the gas bag throughout the experiment.

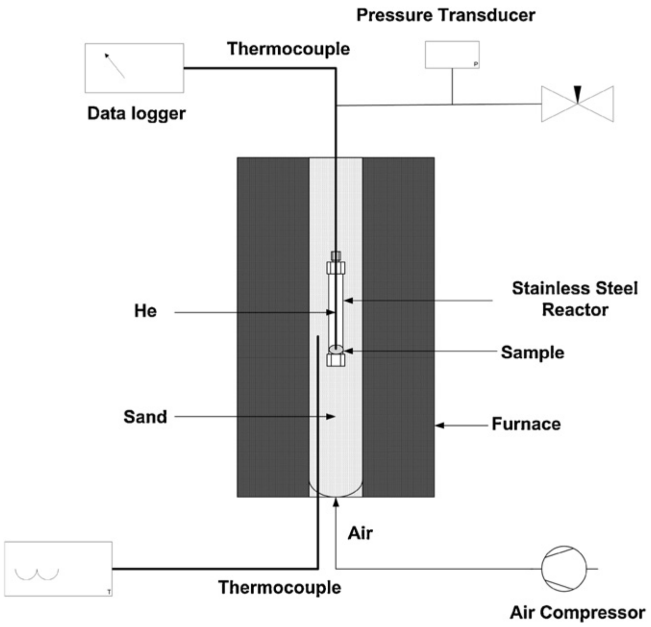

Fig. 1. Schematic diagram of torrefaction under pressure.

After reaching the desired reaction time, the reactor was immersed in water bath in order to stop the reaction immediately. After having cooled to room temperature, the evolved gas was collected by using a gas bag by purging helium into reactor several times. Then, the gas products were analyzed by using the gas chromatography (GC-14B, Shimudzu). The reactor with the sample was dried in the oven for 2–3 h before weighing. The remaining sample was then analyzed by using several apparatus.

2.3. Evolved gas analyses by TG–MS technique

A quadrupole mass spectrometer (Perkin–Elmer, Clarus 500 MS) coupled to the thermobalance (Perkin–Elmer, Pyris1 TGA) was used for the evolved gas analysis during the pyrolysis. The pyrolysis experiments were performed at a heating rate of 10 °C/min up to the final temperature of 800 °C under the helium flow rate of 50 ml/min. To avoid secondary reactions, a probe was placed very close to the sample pan of the thermobalance in the direction of the gas flow. The transfer lines between the TGA and the MS were heated to 200 °C in order to avoid cold spots and thus prevent the condensation of the gaseous products. The signals for mass numbers of 2, 15, 18, 28, and 44 were continuously detected. Then the mass numbers were converted to the concentrations of H_2, CH_4, H_2O, CO, and CO_2 by referring to the calibration curves constructed using the standard gases. The evolving rates of the gaseous products were estimated from the measurements.

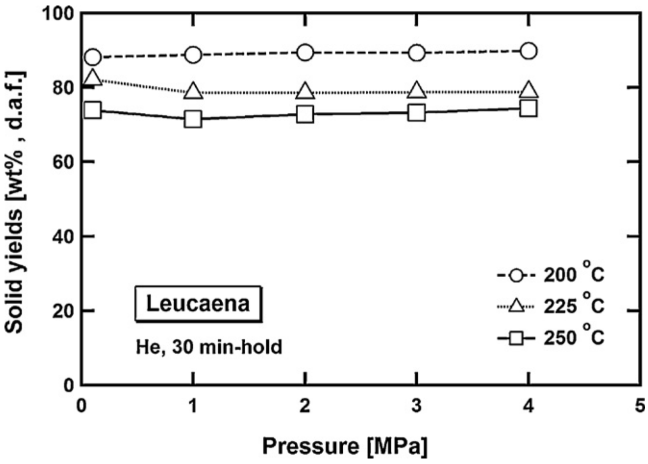

Fig. 2. Solid yields obtained from torrefaction under pressure.

3. Results and discussion

3.1. Product yields and carbon distributions through the torrefaction

It is well-known that the torrefaction temperature is very important parameter affecting the solid yield and their properties, then in this study, the solid yield was preliminarily investigated by varying temperature from 200 to 250 °C. Fig. 2 shows the solid yields of leucaena after torrefaction at various temperatures and pressures. It was found that the solid yield decreased with increasing torrefaction temperature. For example, the solid yields at atmospheric pressure were 88.2%, 82.2% and 73.9% at 200 °C, 225 °C and 250 °C, respectively. With increasing pressure, the solid yields were found to increase gradually from atmospheric conditions. They, for example, increased from 88.2% to 89.9% during torrefaction at atmospheric pressure to 4 MPa for leucaena torrefied at 200 °C. On the other hand, at 225 °C and 250 °C, the solid yield was found to decrease when the pressure was increased to 1 MPa. However, it was found to increase by a few percentages later after the pressure was raised. These behaviors showed the strong effect of pressure by enhancing the decomposition of leucaena during the rising of pressure to 1 MPa at the temperature higher than 225 °C. However, at elevated pressure from 1 MPa to 4 MPa, the condensation of released volatile was promoted by the rising of pressure showing the continue increase in solid yield.

From the preliminary results, it was found that the relative high yield of torrefied leucaena (higher than 70%), was achieved by the torrefaction around 250 °C, then we judged the temperature of 250 °C to be considered as the highest torrefaction temperature for further analyses in this study.

Fig. 3 shows the distributions of products through the torrefaction at various reaction temperatures and pressures. Around 0.7–9.0% CO_2 were also produced progressively with the increase in torrefaction temperatures and pressures. In this study, however, the measurement of H_2O was unavailable since its rapid condensation took place inside the reactor during rapid quenching of reactor in water. The amounts of H_2O and condensables were therefore shown together as the difference values from over all quantified products. However, since large amount of H_2O, which is mainly from hemicellulose decomposition [30], was produced during torrefaction and also increased with torrefaction temperatures, the distributions of carbon in the products were judged to be more informative. The distributions of carbon in the products were estimated from the yields of carbon contains in each products, and they are shown in Fig. 4. Now, the difference values became smaller and they can be considered as only carbon found in the condensables. From the experiments, it was found that around 79.6–93.7% of carbon was recovered in the solid product. With the increase in torrefaction pressure, carbon in solid product was found to increase continuously while the carbon in condensables showed the opposite trend. For example, at 250 °C, carbon going to solid increased from 79.6% to 82.4%, 86.1%, 87.2% and 92.6% for the torrefaction at atmospheric pressure, 1 MPa, 2 MPa, 3 MPa and 4 MPa, respectively. On the other hand, carbon going to condensables which was found large amount at atmospheric pressure (18.9%) almost disappeared (1.8% left) at torrefaction pressure of 4 MPa. In another word, the different product found from torrefaction at 250 °C, 4 MPa

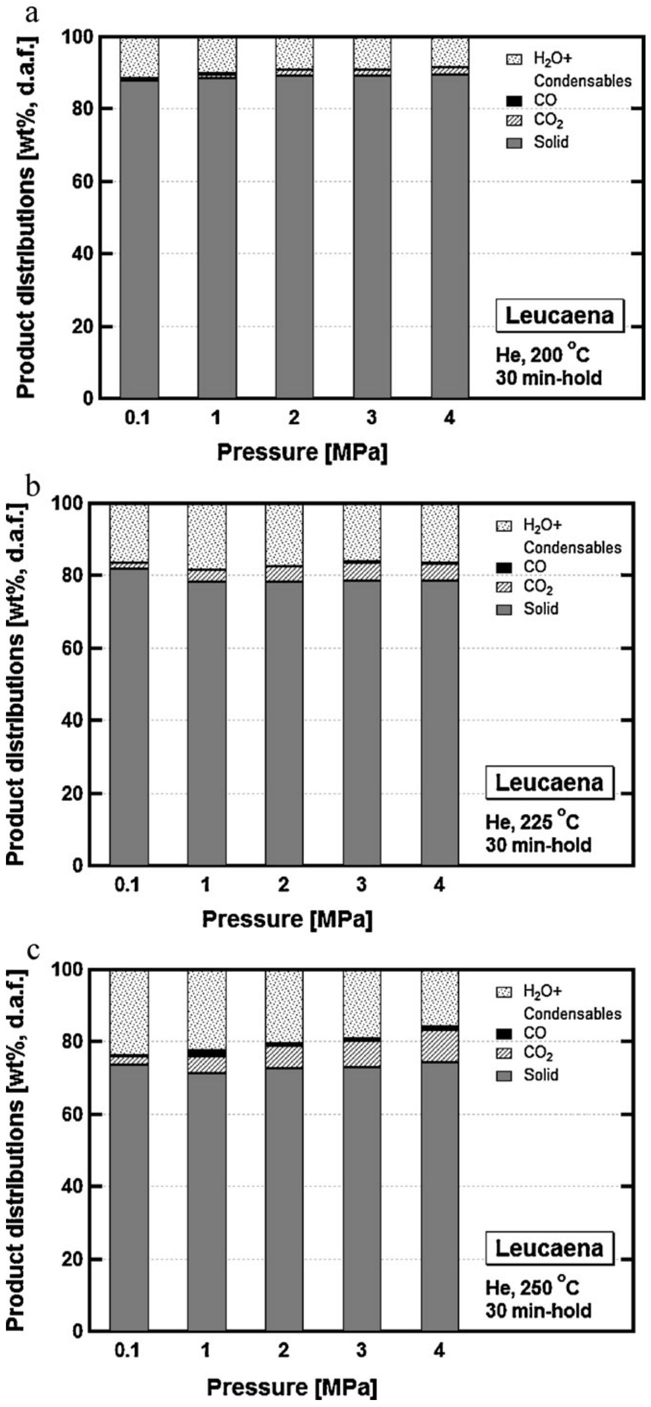

Fig. 3. Product distributions of leucaena torrefied under pressure at (a) 200 °C, (b) 225 °C and (c) 250 °C.

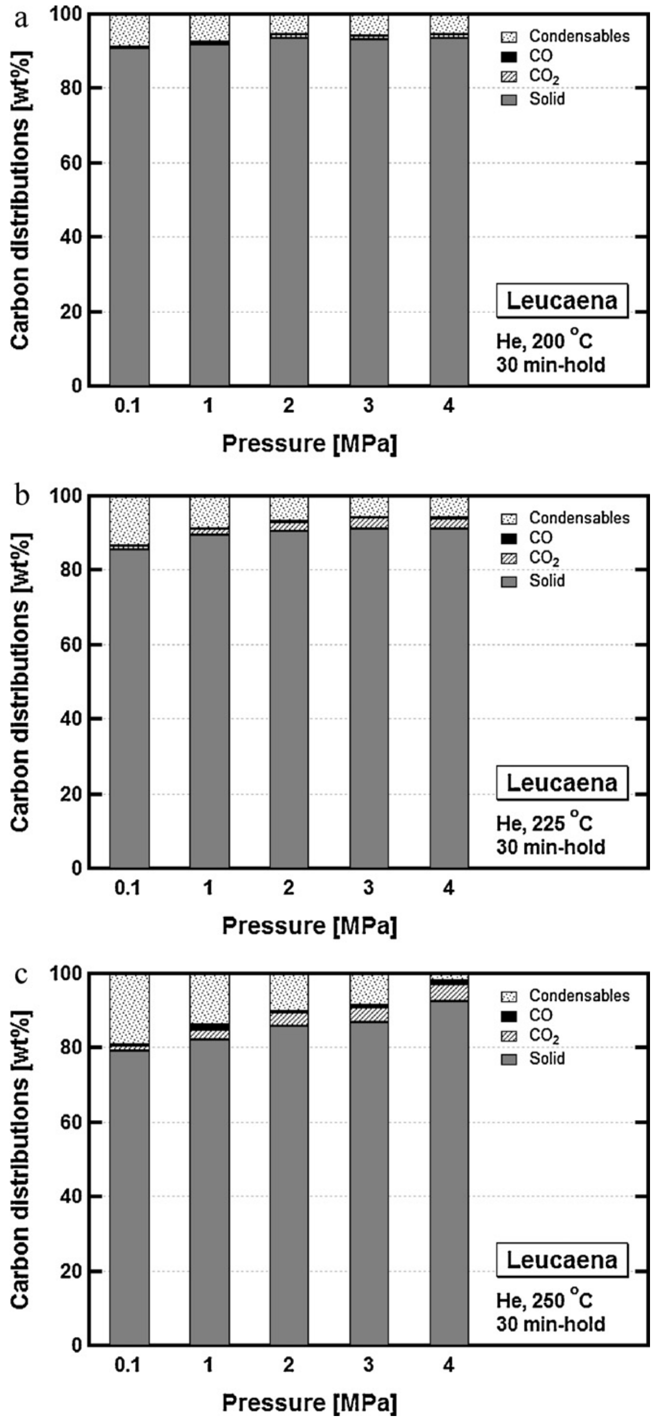

Fig. 4. Carbon distributions of leucaena throughout torrefaction under pressure at (a) 200 °C, (b) 225 °C and (c) 250 °C.

(Fig. 3) was almost H_2O. Therefore, it can be concluded that during torrefaction we can recover the higher carbon by increasing the pressure.

3.2. *Chemical properties of leucaena torrefied under pressure*

Table 1, 2 show the proximate and ultimate analyses of raw and torrefied leucaena preparing at elevated temperatures and pressures. At increasing torrefaction temperatures, the volatile matter was found to decrease significantly. On the other hand, the fixed carbon was also found to increase substantially with increasing temperature. These behaviors were also observed for higher pressure conditions. The decreasing of volatile matter and increasing of fixed carbon were observed at the rising of pressure (see Table 1). The decreasing of volatile matter and increasing of fixed carbon with the rising of pressure were more pronounced at torrefaction at 250 °C: the volatile matter decreased to 60.0% and the fixed carbon increased to 38.2% at torrefaction pressure of 4 MPa. In this study, the higher heating value (HHV) was obtained by using Friedl et al.'s formula [31] as follows:

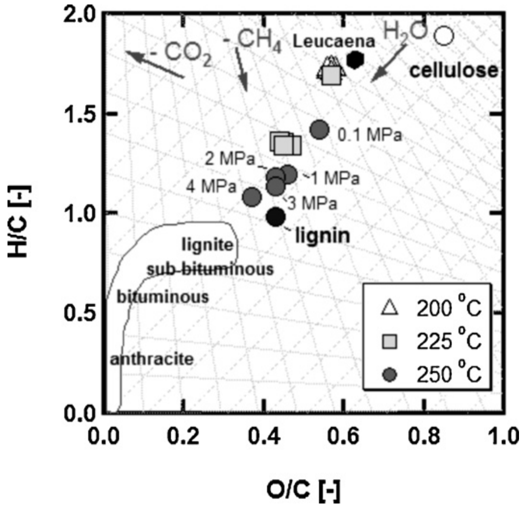

Fig. 5. H/C and O/C diagram of leucaena and leucaena torrefied under pressure.

$$\text{HHV(MJ/kg)} = 5.22\text{C}^2 - 319\text{C} - 1647\text{H} + 38.6\text{CH} + 133\text{N} + 21,028 \qquad (1)$$

where C represents percentage of carbon content, H represents percentage of hydrogen content and N represents nitrogen content in the structure determined on a dry-ash-free basis.

As Table 2 shows, the carbon content was found to increase significantly with the increase in torrefaction temperatures and pressures. For the hydrogen content, approximately 1% decrease was observed while the nitrogen content did not change much with the increase in torrefaction temperatures. The oxygen content appeared to decrease significantly with the increase in torrefaction temperature, and the decreasing of the oxygen content seemed to be more pronounced when prepared at higher pressures: the oxygen content was found to decrease from 38.9% to 31.1% of atmospheric pressure to 4 MPa at 250 °C, respectively. These resulted in the increase in HHV of torrefied leucaena with the increase in torrefaction temperature and pressure. The increase in torrefaction pressure did not affect much the nitrogen content in the torrefied leucaena. It was noted that the HHV of leucaena increased as large as 17.8% when the pressure increased from atmospheric to 4 MPa at torrefaction temperature of 250 °C.

Next, in order to examine the fuel properties of torrefied leucaena, the elemental composition of leucaena as well as leucaena torrefied at various conditions were also plotted on H/C vs. O/C diagram as shown in Fig. 5. From Fig. 5 raw leucaena was plotted at H/C = 1.77 and O/C = 0.63 while the torrefied leucaena were plotted at lower value ratios, lying along the dehydration reaction line ($-H_2O$). The H/C and O/C values of torrefied leucaena, for example, move from H/C = 1.42 and O/C = 0.54 to H/C = 1.08 and O/C = 0.37 when the torrefaction pressure increased from atmospheric to 4 MPa at 250 °C, respectively. This indicated that the torrefaction of leucaena proceeded through the coalification process resulted in the values of H/C and O/C very close to lignite. The position of H/C and O/C values also showed that the

Table 1
Proximate analysis of leucaena and torrefied leucaena and the solid yield obtaining from the torrefaction process.

Sample(torrefied leucaena)	Proximate analysis (%, dry basis)			Solid yield(%, d.a.f.)
	Volatile matter	Fixed carbon	Ash	
Leucaena	87.3	12.2	0.5	100
Conditions [°C-MPa]				
200-0.1	86.9	12.6	0.5	88.2
200-1	84.9	14.5	0.6	88.8
200-2	84.1	15.4	0.5	89.4
200-3	83.7	15.7	0.6	89.3
200-4	83.0	16.0	1.0	89.9
225-0.1	83.0	15.8	1.2	82.2
225-1	79.6	19.5	0.9	78.6
225-2	76.1	22.7	1.2	78.6
225-3	77.6	21.5	0.9	78.8
225-4	77.3	21.6	1.1	78.9
250-0.1	81.6	17.3	1.1	73.9
250-1	71.3	27.8	0.9	71.5
250-2	67.5	30.8	1.7	72.9
250-2	66.2	32.3	1.5	73.3
250-4	60.0	38.2	1.8	74.4

Table 2
Ultimate analysis and the higher heating value (HHV) of leucaena and torrefied leucaena.

Sample (torrefied leucaena)	Ultimate analysis [wt.%, dry-ash-free basis]						HHV [MJ/kg, d.a.f.]
	C	H	N	O (dif.)	O/C	H/C	
leucaena	50.1	7.4	0.7	41.8	0.63	1.77	20.4
Conditions [°C-MPa]							
200-0.1	51.7	7.4	0.7	40.2	0.58	1.72	21.2
200-1	52.0	7.5	0.7	39.8	0.57	1.73	21.4
200-2	52.5	7.5	0.7	39.3	0.56	1.71	21.6
200-3	52.4	7.5	0.7	39.4	0.56	1.72	21.6
200-4	52.2	7.4	0.7	39.7	0.57	1.70	21.4
225-0.1	52.4	7.4	0.7	39.2	0.57	1.69	21.5
225-1	57.2	6.4	0.8	35.6	0.47	1.34	23.6
225-2	57.9	6.5	0.8	34.8	0.45	1.35	24.0
225-3	58.2	6.6	0.8	34.4	0.44	1.36	24.2
225-4	58.1	6.5	0.8	34.6	0.45	1.34	24.1
250-0.1	54.0	6.4	0.7	38.9	0.54	1.42	21.9
250-1	57.7	5.7	0.9	35.7	0.46	1.19	23.4
250-2	59.2	5.8	0.9	34.1	0.43	1.18	24.3
250-3	59.6	5.6	0.9	34.9	0.43	1.13	24.3
250-4	62.3	5.6	1.0	31.1	0.38	1.08	25.8

leucaena torrefied under high pressure gave the better elemental fuel properties than that of leucaena torrefied at atmospheric pressure.

Next, in order to evaluate the suitable condition for torrefaction, the calculation of energy yield which is one of the important parameters was then examined. Fig. 6 shows mass and energy yields of torrefied leucaena as a function of pressure. The energy yield is defined as follows:

$$\text{Energy yield} = \frac{\text{mass yield} \times \text{HHV}_{\text{torrefied sample}}}{\text{HHV}_{\text{raw sample}}} \qquad (2)$$

At the same torrefaction temperature, it was found that the energy yields increased with the increase in the torrefaction pressure. For example, when the torrefaction pressure increased (0.1–4 MPa) at 200 °C, the mass and energy yield were found to increase from 88.2% to 89.9% and 91.6 to 95.0%, respectively. As large as 94.3% of energy yield, for example, was achieved with the mass yield of 74.4% for the torrefaction at 250 °C and 4 MPa. In another words, we can reduce the sample weight by 25.6% while losing energy only 5.7%. These results were considered in the viewpoint of more efficient transportation of torrefied leucaena without losing much energy.

3.3. *Thermal analyses*

As the results in the previous section showed, since the elemental properties of torrefied leucaena was found attractive from the torrefaction at 250 °C, thus the analyses hereafter will focus on this torrefaction temperature. The thermal analyses include the pyrolysis behaviors performing in nitrogen atmosphere by using TG–MS technique. The combustion behaviors of leucaena torrefied under pressure were also examined in air by using TGA.

3.3.1. *Pyrolysis behaviors of leucaena torrefied under pressure*

Fig. 7 shows the weight decreasing curves of raw and torrefied leucaena prepared at 250 °C by varying torrefaction pressure, during heating to 800 °C at a heating rate of 10 °C/min in flow of nitrogen. In order to compare with the raw leucaena, the weight of the torrefied leucaena was normalized by multiplying the weight with the yield of the torrefied leucaena. From the experiments, the significant difference of weight decreasing profiles among raw leucaena, leucaena torrefied at atmospheric pressure and leucaena torrefied at elevated pressure was observed. The weight of raw leucaena started to decrease around 150 °C and decreased rapidly at around 250–320 °C. After that, the weight decreased gradually when increasing the temperature to 800 °C. The weight of leucaena torrefied at atmospheric pressure started to decrease at the temperature higher than 200 °C, which was very close to

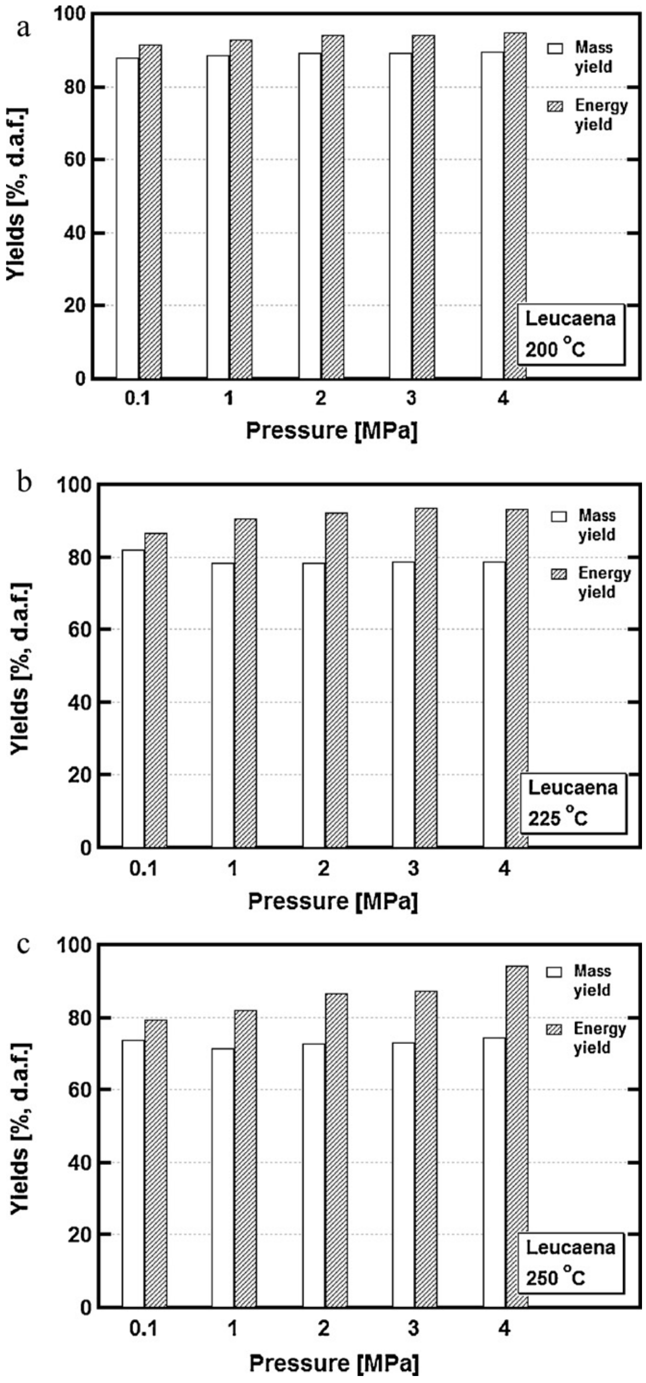

Fig. 6. Mass and energy yields of leucaena torrefied under pressure at (a) 200 °C, (b) 225 °C and (c) 250 °C.

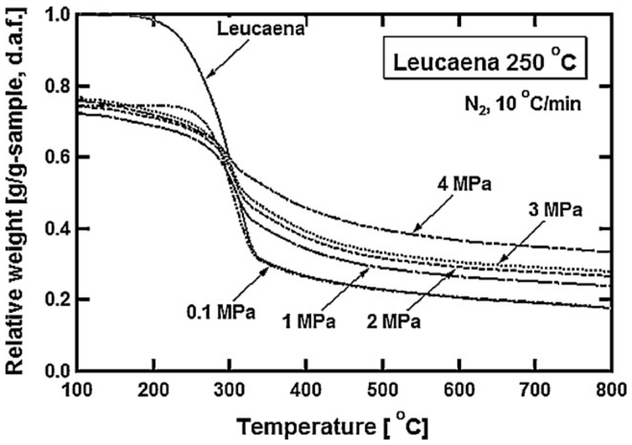

Fig. 7. Weight decreasing curves of leucaena and leucaena torrefied under pressure at 250 °C.

that of final torrefaction temperature, then decreased rapidly at around 250–320 °C. On the other hand, the weight of leucaena torrefied at high pressure (1–4 MPa) showed the different behaviors. The weight of leucaena torrefied at high pressure started to decrease at temperature lower than 200 °C and decreased rapidly at around 250–400 °C. After that, the weight decreased gradually when increasing the temperature to 800 °C. Moreover, it was found that the char yield at 800 °C for the leucaena torrefied at high pressure was higher than the char yield of raw leucaena and the leucaena torrefied at atmospheric pressure. The char yield at 800 °C for the leucaena torrefied at atmospheric pressure was almost the same as that of the raw leucaena. On the other hand, the char yield at 800 °C for the leucaena torrefied at high pressure increased with the increase in torrefaction pressure: the char yield increased from 17.5% to 33.2% when increasing the pressure from 1 MPa to 4 MPa. The increase in char yield could be explained by the progress of the cross-linking reactions occurred during the pyrolysis. More discussion will be shown in the next section. These results suggested that the structure of leucaena was changed by the torrefaction under pressure and the cross-linking reactions during the pyrolysis were enhanced by the pressure during the torrefaction resulting in increase in char yields.

3.3.2. Product distributions and gas formation rates through the subsequent pyrolysis of leucaena torrefied under pressure

Next, the product distributions throughout the pyrolysis at 600 °C for raw leucaena and leucaena torrefied at 250 °C under pressure were investigated as shown in Fig. 8. The product distributions of the torrefied leucaena were normalized with the solid yield obtaining from the torrefaction for each studied conditions. It was found that the char yield of the raw leucaena and the leucaena torrefied at atmospheric pressure were almost the same. On the other hand, the char yield significantly increased with the increase in pressure during the torrefaction. The yield of CO_2 decreased significantly with the increase in pressure during torrefaction: it decreased from 15.2% to 5.8% when increased the torrefaction pressure from atmospheric pressure to 4 MPa. The yield of CO increased with the increase in torrefaction pressure: it increased from 2.6% to 7.0% when increased the torrefaction pressure from atmospheric

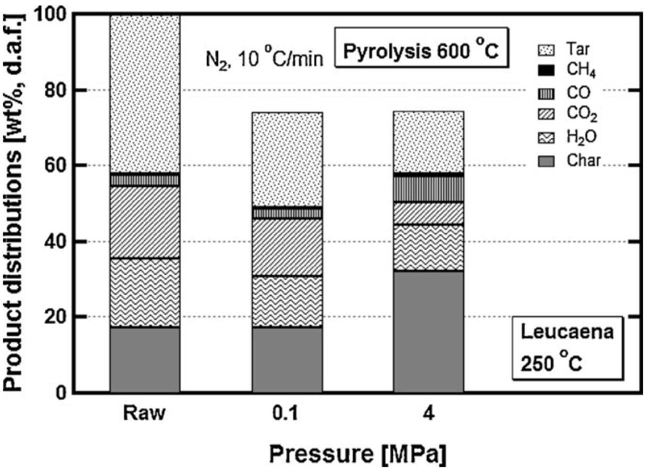

Fig. 8. Product distribution throughout the pyrolysis at 600 °C for raw leucaena and leucaena torrefied under various pressures at 250 °C.

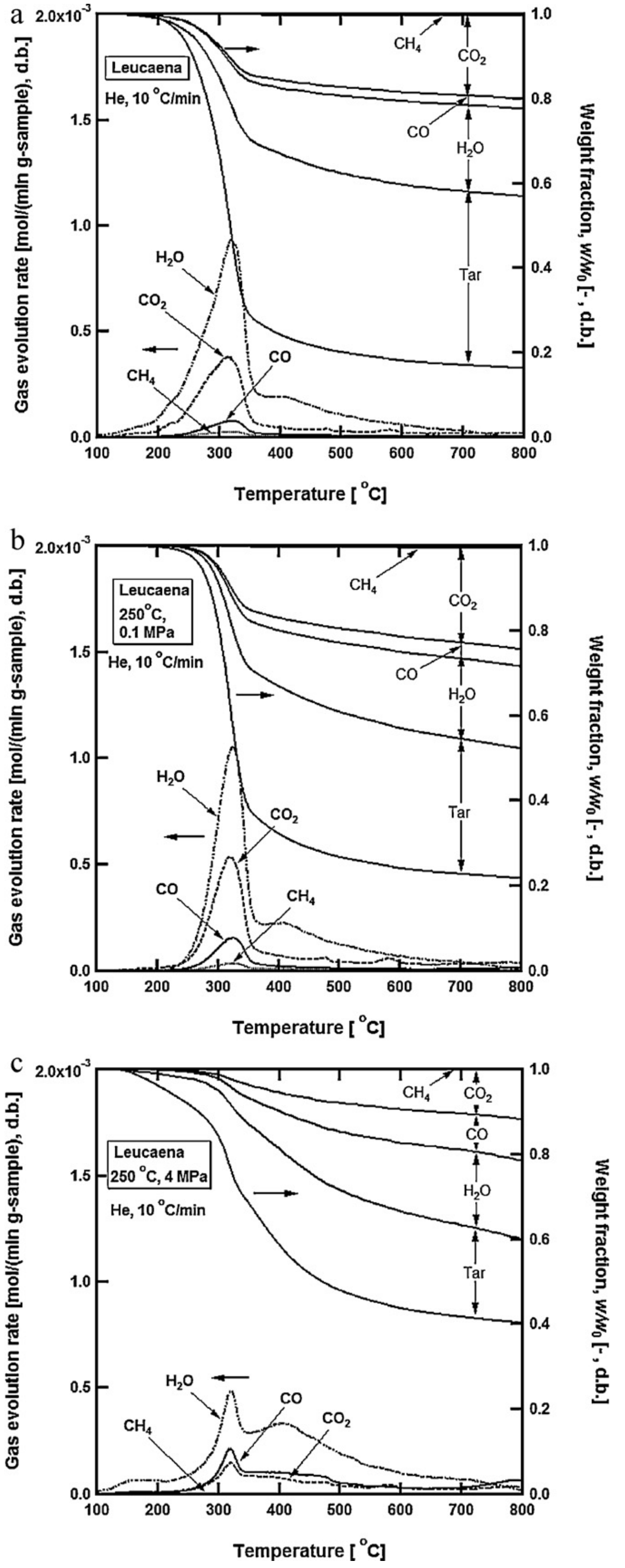

Fig. 9. TG–MS profiles during subsequent pyrolysis of (a) leucaena, (b) leucaena torrefied at atmospheric pressure and (c) leucaena torrefied at 4 MPa.

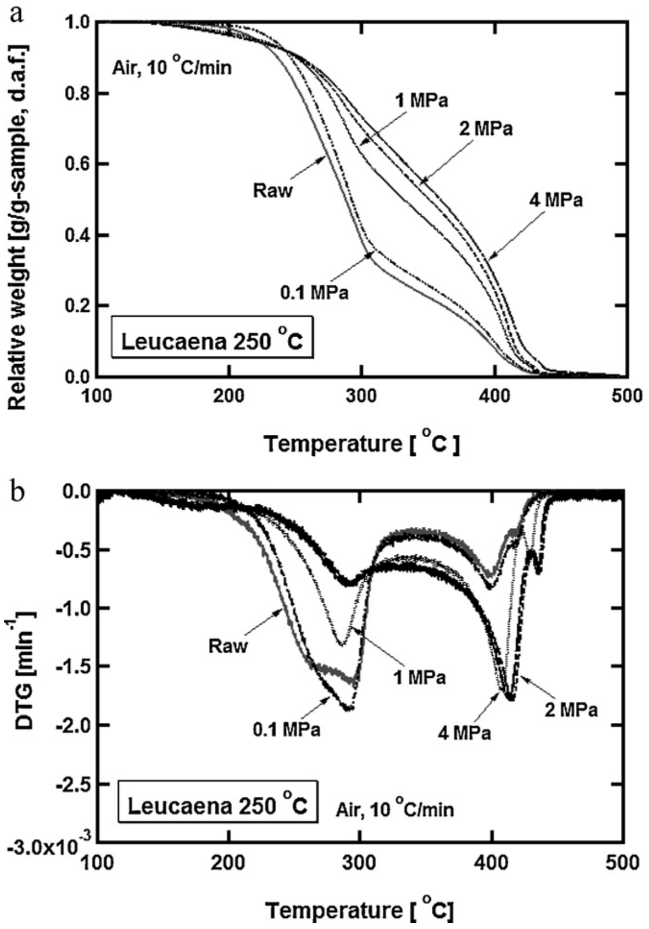

Fig. 10. Weight decreasing curves (a) and DTG curves (b) during combustion in TGA of leucaena and leucaena torrefied under pressure.

pressure to 4 MPa. H_2O was found to decrease progressively with the increase in torrefaction pressure: it decreased from 18.4% to 13.6% and 12.1% for raw leucaena, leucaena torrefied at atmospheric pressure and leucaena torrefied at 4 MPa, respectively. In addition, the significant reduction of tar with the increasing of pressure was also observed. The tar yield reduced from 41.9% for the pyrolysis of the raw leucaena to 25.1% and 16.5%, for leucaena torrefied at atmospheric pressure and 4 MPa, respectively. These results were judged to be due to the enhancing of cross-linking reactions by the torrefaction under pressure as discussed in Section 3.3.1.

Then the comparisons of the gas formation rates during the pyrolysis have been examined. As shown in Fig. 9, the gas evolution rate profiles of raw leucaena and leucaena torrefied at various pressures were significantly different. The highest evolution rate was in the decomposition range of around 300–350 °C. H_2O was found to be the highest gas yield and gas evolution rate during the pyrolysis. All gaseous products started to evolve at temperature higher than 250 °C for leucaena torrefied at atmospheric pressure. On the other hand, H_2O started to evolve at 100 °C for the leucaena torrefied at 4 MPa. Moreover, it can be seen that some amounts of tar also evolved at temperature below 200 °C. This evolved tar might be from the condensable compounds condensing on the torrefied leucaena during the torrefaction.

3.3.3. Combustion characteristic of leucaena torrefied under pressure

The combustion behaviors of raw and torrefied leucaena were examined by using TGA. Panel a in Fig. 10 shows the weight decreasing curves during combustion of raw leucaena and leucaena torrefied at 250 °C in dry-ash-free basis. It was found that the weight decreasing curves for leucaena torrefied under pressure started to decrease of around 150 °C which was earlier than that of torrefied at atmospheric pressure. The significant weight decrease of leucaena torrefied under pressure occurred during 250–380 °C and then the weight decreased sharply at 400–450 °C. The weight decreasing curves for the leucaena torrefied under pressure shifted to higher temperature with the increase in torrefaction pressure. On the other hand, the weight decreasing curve for leucaena torrefied at atmospheric pressure showed the significant decrease at 210–300 °C and 300–450 °C which was similar to that of raw leucaena.

Panel b in Fig. 10 showed the DTG curves during the combustion of raw leucaena and torrefied leucaena. It was found that the main two sharp peaks occurred at 250–300 °C and 380–400 °C, respectively. The first peak could be referred to the main combustion of volatile matter from pyrolysis step while the second peak could be suggested to the char combustion step. At the first step (lower than 350 °C), the combustion rate of leucaena torrefied under pressure was lower than that of the raw and leucaena torrefied at atmospheric pressure. This is due to the relative low amounts of volatile matter in the leucaena torrefied under pressure. However, the substantial high combustion rate occurred at the char combustion step (higher than 380 °C) for leucaena torrefied under pressure. It was higher than those of raw leucaena and leucaena torrefied at atmospheric pressure.

4. Conclusions

In this study, the upgrading of leucaena by torrefaction under pressure at 0.1–4 MP and vary the temperature from 200 to 250 °C was examined. During the torrefaction, the yield of torrefied leucaena was found to decrease with the increase in torrefaction temperature, whereas the yield of torrefied leucaena increased with the increase in torrefaction pressure. From the elemental analyses, the higher carbon content in torrefied leucaena can be achieved by the rising of torrefaction pressure. As large as 92.6% of carbon was recovered in the torrefied leucaena prepared at 250 °C and 4 MPa. While the oxygen content decreased to 31.1% for the torrefied leucaena prepared at 250 °C and 4 MPa. The higher heating value (HHV) increased significantly when compared to that of torrefied at atmospheric pressure. As large as 94.3% of energy yield was achieved with the mass yield of 74.4% for the torrefaction at 250 °C and 4 MPa. From the subsequent pyrolysis and combustion in TGA, leucaena torrefied under pressure showed the difference of weight decreasing curves comparing to that of torrefied at atmospheric pressure. It was found that the weight of leucaena torrefied at high pressure started to decrease at temperature lower than 200 °C. The char yield at 800 °C for the leucaena torrefied at high pressure increased with the increase in torrefaction pressure. These results suggested that the structure of leucaena was changed by the torrefaction under pressure and the cross-linking reactions during the pyrolysis were enhanced by the pressure during the torrefaction resulting in increase in char yields. The substantial increase in char combustion rate was also found for leucaena torrefied under pressure. These results showed that the leucaena could be upgraded efficiently by the torrefaction under pressure at 1–4 MPa.

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